

APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

DEFORMABLE MEMS MIRROR

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DEFORMABLE MEMS MIRROR

CROSS-REFERENCE TO RELATED APPLICATIONS

The subject matter of this application is related to that of U.S. Patent Application
5 No. 10/394,359, identified by attorney docket No. Neilson 13, filed March 21, 2003,
entitled "Dispersion Compensator," and referred to hereafter as "the Neilson application,"
the teachings of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

10 Field of the Invention

The present invention relates to optical communication equipment and, more
specifically, to micro-electromechanical (MEMS) devices for use in such equipment.

Description of the Related Art

15 Adaptive optics is a field of optics dedicated to the improvement of optical signals
using information about signal distortions introduced by the environment in which the
optical signals propagate. An excellent introductory text on the subject is given in
"Principles of Adaptive Optics" by R. K. Tyson, Academic Press, San Diego, 1991, the
teachings of which are incorporated herein by reference.

20 A representative adaptive optical element is a movable deformable mirror that
may be used, for example, in an optical communication system designed to route optical
signals. In such an application, the mirror is tilted to direct the optical signal to a selected
output port. In addition, the mirror may be deformed to compensate for possible signal
distortions accrued during prior signal propagation. The mirror deformation is chosen
25 such that the distortions are significantly reduced, thus improving receiver performance.
However, one problem with such prior-art systems is that the mirror rotation and
deformation may be disadvantageously coupled.

SUMMARY OF THE INVENTION

30 Problems in the prior art are addressed, in accordance with the principles of the
present invention, by a MEMS device having a deformable mirror, for which the mirror
deformation is decoupled from and hence independent of the mirror rotation. This is

achieved by employing a deformation actuator that moves so as to decouple the mirror rotation and deformation. In representative embodiments, the MEMS device includes (1) a deformable plate having a reflective surface, the plate being movably connected to a substrate, and (2) a deformation actuator mounted on the plate such that, when the plate moves with respect to the substrate, the actuator moves together with the plate without any changes in the relative position of the plate and the actuator. In one embodiment, the actuator has (i) a first electrode, one end of which is attached to an edge of the plate and (ii) a second electrode attached to an interior portion of the plate. When a voltage differential is applied between the first and second electrodes, an unattached end of the first electrode moves with respect to the second electrode, thereby applying a deformation force to the plate. Advantageously, motion and deformation of the deformable plate in such MEMS device are decoupled.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a schematic cross section of a prior-art device having a deformable membrane;

Fig. 2 illustrates a perspective three-dimensional view of a MEMS device having a deformable membrane according to one embodiment of the invention;

Figs. 3A-C show schematic top and side views of a MEMS device having a deformable plate according to another embodiment of the present invention;

Figs. 4A-H illustrate representative fabrication steps of the MEMS device shown in Fig. 3 according to one embodiment of the invention; and

Fig. 5 shows a top view of a MEMS device according to yet another embodiment of the present invention.

DETAILED DESCRIPTION

Reference herein to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

Fig. 1 shows a representative prior-art device **100** having a deformable light-reflecting membrane **102** mounted on a movable support structure **104**. Support structure **104** is attached to a corresponding motion actuator (not shown) that can rotate said support structure (together with membrane **102**) with respect to a substrate **140**, e.g., as indicated by the “rotation” arrow in Fig. 1. In addition, device **100** has a deformation actuator comprising a plurality of electrodes **106** attached to substrate **140**. Each electrode **106** can be individually biased by applying a voltage differential between that electrode and membrane **102** (typically at ground potential). For example, when electrode **106-1** is biased, an attractive electrostatic force (F) is exerted between that electrode and membrane **102** causing the membrane, initially flat, to deform into the shape indicated in Fig. 1.

One problem with device **100** is that rotation of support structure **104** changes the relative position of membrane **102** and electrodes **106**, which changes the deformation force field acting upon the membrane and consequently the shape of the membrane. Thus, rotation and deformation of membrane **102** in device **100** are disadvantageously coupled.

Fig. 2 illustrates a perspective three-dimensional view of a MEMS device **200** according to one embodiment of the present invention. Device **200** has a deformable membrane **202** attached to a support structure **204** in a cantilevered configuration, which membrane can be deformed using a deformation actuator **206** having two electrodes **206a-b**. Electrode **206a** is attached to a support beam **208** located at an edge of membrane **202**. When membrane **202** is in a non-deformed (i.e. flat) state, electrode **206a** extends parallel to the surface of the membrane such that there is a small gap between the membrane surface and the electrode. Electrode **206b** is Π -shaped and mounted on a pair of spacers **210** such that (i) similar to electrode **206a**, electrode **206b** extends parallel to the membrane surface and (ii) the gap between the membrane surface and electrode **206b** is greater than the gap between the membrane surface and electrode **206a**.

When there is no voltage differential between electrodes **206a-b**, the membrane is flat and the electrodes are parallel to the membrane surface and vertically offset with respect to each other. However, when electrode **206b** is biased with respect to electrode **206a**, an attractive electrostatic force generated between the electrodes pulls the free

(unattached) end of electrode **206a** upward thereby deforming membrane **202** as shown in Fig. 2. The elastic spring force produced due to the membrane deformation acts to counterbalance the electrostatic force.

In one embodiment, support structure **204** is movably mounted on a substrate (not shown). When support structure **204** moves (e.g., rotates) with respect to the substrate, membrane **202** and actuator **206** move together with the support structure without any changes in the relative position of the membrane and the actuator. Thus, rotation and deformation of membrane **202** in device **200** are advantageously decoupled.

Figs. 3A-C show a MEMS device **300** according to another embodiment of the present invention. More specifically, Fig. 3A shows a top view of device **300**, and Figs. 3B-C show side views of device **300** along the view directions indicated by the “view” arrows in Fig. 3A. Device **300** has (i) a movable deformable plate **302** supported on a substrate **304** by a pair of serpentine springs **312a-b** and (ii) two electrostatic actuators **306** and **316**. Actuator **306** is adapted to deform plate **302**, e.g., as indicated in Fig. 3C, and actuator **316** is adapted to rotate plate **302** with respect to substrate **304**, e.g., as indicated by the “rotation” arrow in Fig. 3B.

Actuator **306** is based on a similar concept as actuator **206** (Fig. 2) and comprises a plurality of electrodes **306a** and a plurality of electrodes **306b**. Each electrode **306a** is similar to electrode **206a** and is attached to a corresponding support beam **308** located at an edge of plate **302** such that the electrodes attached to beam **308a** are interleaved with the electrodes attached to beam **308b**. Electrodes **306a** are electrically connected to plate **302**, which in turn is electrically connected to substrate **304** via spring **312b**. In a preferred configuration, electrodes **306a**, plate **302**, and substrate **304** are at ground potential. Each electrode **306b** is similar to electrode **206b** and is mounted on a corresponding pair of spacers attached to plate **302** near the center axis of the plate. Electrodes **306b** are electrically isolated from plate **302** using the electrical insulation of the spacers and can be electrically biased using a contact pad **320a** to which they are electrically connected via a conducting trace **324**, spring **312a**, and a conducting trace **322a**.

When there is no voltage differential between electrodes **306a-b**, plate **302** is flat and the electrodes are parallel to the plate surface. When electrodes **306b** are biased with respect to electrodes **306a**, e.g., by a bias voltage applied to pad **320a**, an attractive

electrostatic force generated between the electrodes pulls the suspended (unattached) ends of electrodes **306a** upward, thereby deforming plate **302** as shown in Fig. 3C. It can be shown that plate **302** has a curvature value substantially proportional to the square of the bias voltage, where curvature is quantified as a reciprocal curvature radius.

5 Actuator **316** is a fringe-field (FF) actuator similar to FF actuators disclosed in commonly owned U.S. Patent Application No. 10/261,088, filed on 9/30/2002 and entitled "Monolithic Two-Axis MEMS Device for Optical Switches," the teachings of which are incorporated herein by reference. Briefly, actuator **316** has two electrodes **316a-b**. Electrode **316a** is an extension of plate **302** and therefore is at ground potential
10 in the configuration described above. Electrode **316b** is a stationary electrode mounted on substrate **304** and located in proximity to electrode **316a** as shown in Figs. 3A-B. Electrode **316b** is electrically isolated from substrate **304** using electrical insulation of an underlying thin insulating layer **332** and can be electrically biased using a contact pad **320b** electrically connected to the electrode via a conducting trace **322b**.

15 When there is no voltage differential between electrodes **316a-b**, springs **312** keep plate **302** in a (horizontal) position shown in Fig. 3B. However, when electrode **316b** is biased with respect to electrode **316a**, e.g., by a bias voltage applied to pad **320b**, an attractive electrostatic force generated between the electrodes pulls electrode **316a** upward, thereby deflecting plate **302** downward as indicated by the "rotation" arrow in
20 Fig. 3B. It should be noted that, when plate **302** moves (e.g., rotates) with respect to substrate **304**, actuator **306** moves together with the plate without any changes in the relative positions of electrodes **306a-b**. Thus, rotation and deformation of plate **302** in device **300** are advantageously decoupled similar to the rotation and deformation of membrane **202** in device **200** (Fig. 2).

25 One possible application of device **300** is described in the above-cited Nielson application. Briefly, Nielson teaches a dispersion compensator having a diffraction grating operating in reflection and optically coupled to a mirror array, in which different mirrors receive light corresponding to different communication channels. For each channel, a desired group delay value is produced by selecting the curvature of the
30 corresponding mirror. A compensator employing a plurality of independently addressable, variable-curvature mirrors, similar to plates **302** of device **300**, is capable of generation of variable, channel-specific group delays between about +400 and -400

ps/nm while maintaining transmission-band uniformity of better than about ± 0.4 dB over a channel bandwidth of about 60 GHz.

Figs. 4A-H illustrate representative fabrication steps of device **300** (Fig. 3) according to one embodiment of the invention. More specifically, Figs. 4A-H show top views (similar to that shown in Fig. 3A) of device **300** during those fabrication steps.

Referring to Fig. 4A, in one embodiment, fabrication of device **300** begins with a silicon-on-insulator (SOI) wafer having (i) two silicon layers, i.e., substrate layer **304** (see also Fig. 3A) and an overlayer **404**, and (ii) an insulating silicon oxide layer (not visible), which electrically isolates overlayer **404** from substrate layer **304**. Conducting traces **322a-b** and contact pads **320a-b** are defined in overlayer **404** using grooves that may be formed using reactive etching, which stops at the silicon oxide layer. The grooves are schematically shown in Fig. 4A by the solid lines outlining traces **322a-b** and pads **320a-b**.

Referring to Fig. 4B, first, a thin (e.g., 0.1 μm) silicon nitride layer **332** (see also Fig. 3A) is deposited onto overlayer **404**. Then, layer **332** is patterned and etched (i) to form an opening **434** for a future via structure that provides electrical contact between trace **322b** and electrode **316b** (not formed yet, see Fig. 3A) and (ii) to expose a portion **406** of overlayer **404** for the processing step illustrated in Fig. 4C. The processing corresponding to Fig. 4B can be implemented using chemical vapor deposition and reactive etching, which stops at silicon overlayer **404**.

Referring to Fig. 4C, plate **302**, electrode **316a**, conducting trace **324**, and springs **312a-b** are defined in portion **406** of overlayer **404** using reactive etching similar to that corresponding to Fig. 4A. Although the two-step patterning of overlayer **404** illustrated by Figs. 4A and 4C is advantageous in that it guards against possible residual silicon-nitride deposits, e.g., inside the fine groove structure that defines springs **312**, with due care, said patterning may be implemented using a single patterning step.

Referring to Fig. 4D, first, a thin (e.g., 1 μm) silicon oxide layer **432** is deposited over the structure of Fig. 4C. Then, layer **432** is patterned and etched to form (i) openings corresponding to pads **320a-b** and to opening **434** (Fig. 4B), (ii) an opening **436** for a future via structure that provides electrical contact between trace **324** and electrodes **306b** (not formed yet, see Fig. 3), and (iii) openings **438a-b** corresponding to beams **308a-b** (not formed yet, see Fig. 3). The processing corresponding to Fig. 4D can be

implemented using chemical vapor deposition and reactive etching, which stops at silicon overlayer **404**.

Referring to Fig. 4E, first, a thin (e.g., 5 μm) poly-silicon layer **442** is deposited over the structure of Fig. 4D. During the deposition process, poly-silicon also fills (i) openings **434** and **436** to form the corresponding via structures and (ii) openings **438a-b** to electrically connect and mechanically attach beams **308a-b** to plate **302**. Then, layer **442** is patterned and etched to define beams **308a-b**, spacers **410**, and the plurality of electrodes **306a**. Spacers **410** are analogous to spacers **210** (Fig. 2) and provide support to electrodes **306b** (not formed yet, see Fig. 3).

Referring to Fig. 4F, first, a thin (e.g., 1 μm) silicon oxide layer **452** is deposited over the structure of Fig. 4E. Then, layer **452** is patterned and etched (i) to expose a portion **446** of layer **442** for the processing step illustrated in Fig. 4G and (ii) to form openings corresponding to spacers **410** and the via structure of (former) opening **436**.

Referring to Fig. 4G, first, a thin (e.g., 5 μm) poly-silicon layer is deposited over the structure of Fig. 4F. During the deposition process, poly-silicon also fills the openings corresponding to spacers **410**. Then, said poly-silicon layer and portion **446** of layer **442** are patterned and etched to define electrode **316b** (see also Fig. 3) and the plurality of electrodes **306b**. In addition, a portion of substrate layer **304** corresponding to the movable parts of device **300** (i.e., plate **302**, springs **312**, and electrode **316a**) is etched away to expose the thin silicon oxide layer located between substrate layer **304** and overlayer **404** (see also Fig. 3A).

Finally, referring to Fig. 4H, exposed portions of various oxide layers are removed (e.g., etched away) to release the movable parts of device **300** and expose contact pads **320a-b**. A thin layer of metal, e.g., gold, is optionally deposited over the bottom side of plate **302** for better reflectivity and over pads **320a-b** for better electrical contact with wire terminals (not shown).

Different etching techniques may be used to fabricate device **300** from the initial SOI wafer. It is known that silicon etches significantly faster than silicon oxide using, e.g., selective reactive ion etching (RIE). Similarly, silicon oxide etches significantly faster than silicon using, e.g., fluorine-based etchants. Additional layers of material (e.g., layers **432** and **442**, Figs. 4D-E) may be deposited using, e.g., chemical vapor deposition. Various parts of device **300** may be mapped onto the corresponding layers using

lithography. Additional description of various fabrication steps may be found in U.S. Patent Nos. 6,201,631, 5,629,790, and 5,501,893, the teachings of which are incorporated herein by reference.

Fig. 5 shows a top view of a MEMS device **500** according to yet another embodiment of the present invention. Device **500** is similar to device **300** (Fig. 3), with analogous elements of the two devices marked with labels having the same last two digits. In particular, device **500** has (i) a movable deformable plate **502** supported on a substrate **504** by a pair of torsion rods **512a-b** and (ii) two electrostatic actuators **506** and **516**. However, one difference between devices **500** and **300** is that actuator **506** is adapted to apply curvature to plate **502** in a circular pattern while actuator **306** is adapted to apply curvature to plate **302** along one direction. In addition, actuator **516** is adapted to tilt plate **502** with respect to substrate **504** in two opposite directions while actuator **316** is adapted to tilt plate **302** with respect to substrate **304** in just one direction. The additional degree of freedom is enabled by electrodes **516b-c**, wherein electrodes **516b** impart rotation onto plate **502** in the direction opposite to that imparted by electrodes **516c**. Device **500** has three contact pads **520a-c** to independently bias electrodes **506b**, **516b**, and **516c**, respectively.

While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications of the described embodiments, as well as other embodiments of the invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

Although fabrication of MEMS devices of the invention has been described in the context of using silicon/silicon oxide SOI wafers, other suitable materials, such as germanium-compensated silicon, may similarly be used. The materials may be appropriately doped as known in the art. Various surfaces may be modified, e.g., by metal deposition for enhanced reflectivity and/or electrical conductivity or by ion implantation for enhanced mechanical strength. Differently shaped membranes, plates, actuators, and/or electrodes may be implemented without departing from the scope and principle of the invention. For example, a deformable plate and the corresponding deformation actuator may be designed to produce uniform curvature across the plate

when the plate is deformed. To enable said uniformity, the actuator and the plate are appropriately shaped such that the force field applied to the plate is commensurate with local stiffness variations present due to the contact areas between the plate and the actuator, e.g., along the centerline and edges of plate **302** in device **300**. Similarly, the

5 plate and the actuator may be adapted to produce deformations having various desirable one- or two-dimensional curvature patterns. Springs may have different shapes and sizes, where the term “spring” refers in general to any suitable elastic structure that can recover its original shape after being distorted. Various MEMS devices of the invention may be arrayed as necessary and/or apparent to a person skilled in the art.

10 Although the steps in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those steps, those steps are not necessarily intended to be limited to being implemented in that particular sequence.